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Health Improvement Path: Ontological Approach to Self-management Support in Personal Health Management Systems

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Abstract

Ontologies have been used for knowledge modeling and reasoning in healthcare domain (e.g., homecare, hospital clinical procedure, mHealth, etc.), but few in a context of self-management in healthcare with no sufficient reasoning rules to specify a systematic health management plan for an individual. In response to such needs, we aim to provide a generic ontology model for organizing the broad range of multidisciplinary knowledge required in personal health management by applying the ontology design patterns as well as for being extensible to more specific activity ontologies (e.g., physical exercises, diet, medication intake, etc.). The scope of a proposed ontology is to classify core concepts and relations in health self-management process and to build axioms for health improvement plans to meet an individual's needs and health capability/maturity level. The proposed ontology is developed based on our previous work, health capability maturity model (HCMM) and can be integrated with existing health-related ontologies for further specification in health management processes.

1. Introduction

Personal Health Management System (PHMS) enables an individual to better manage and monitor one's activities and lifestyle to improve the health outcomes. The convergence of multiple technologies such as information and communication technologies (ICT), mobile health (mHealth), wearable sensors has led to a patient-centered healthcare model. Accordingly, a workflow of such PHMS relies on a considerable amount of healthcare specific knowledge as well as the indispensable integration with different domain knowledge (e.g., technology specific, environmental specific). Building a powerful and interoperable PHMS is a critical issue and for that reason, ontologies have been adopted in healthcare domain. However, effective knowledge discovery and accumulation are hindered by the complexity in analyzing and constructing explicitly sharable structures and concepts of healthcare domain terminologies. Furthermore, most ontologies in healthcare domain focus on (bio)medical knowledge, patient profile, clinical treatment and intervention from healthcare practitioner's perspective, not many from actual patient's perspective. To effectively support self-management in healthcare systems, a variety of ontologies related to health promoting contexts (e.g. behavior change, fitness, wellness, disease, etc.) are required to be merged and aligned with one another. The main purpose of this paper is to develop a generic ontology model in PHMS that allows an individual to set the goals and measure and track one's progress toward defined goals and activities for improvement. The proposed ontology model describes the abstract workflow of HCMM, a self-management process assessment tool that represents the health capability and maturity levels with customizable improvement path, given an individual's lifestyle and preference.

The rest of the paper is organized as follows. Section 2 provides a brief overview of ontologies in health domains and a role of PHMS as a health self-care/management tool. In section 3, we present a proposed approach, followed by section 4, a use case scenario. Finally, the paper concludes, discussing further research directions.

2. Related work

2.1. Self-management in PHMS

Recent studies have proved that the health status and behavior of patients with chronic diseases can be significantly improved by self-care management programs or trainings [1]–[3]. Self-care/self-management support program is to change patients' behavior or to better control diseases by increasing their self-efficacy and educating knowledge. In general, PHMS is a system or an application that is designed to empower individuals in self-healthcare by monitoring, tracking, recording, and promoting

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their own health status and health information (e.g., ubiquitous health management systems (UHMS), mHealth, etc.). With aid of Personal Health Record (PHR), PHMS helps individuals to access, manage, and share health information with related people (e.g., physicians, caregivers) [4] as well as to involve proactively in dealing with their personal health/medical information (e.g., laboratory results, diagnostic images, etc.) and collecting the data of their current health behavior and lifestyle change [5].

PHMS with the convergence of smart biosensors, smartphones, and cloud computing services enables individuals to monitor changes in their vital signs, provide feedback to manage current health status, and maintain an optimal health status [6], [7].

2.2. Ontologies in healthcare

Ontology is a formal, explicit specification of a shared conceptualization [8], which can capture semantic information of concept and instance levels. The effectiveness of the ontological knowledge relies on the quality of the ontology, which can be achieved by consistency, completeness, conciseness, and reusability in organization of terminologies and taxonomies of the domain[9].

As knowledge bases and inference engines, ontologies have been adopted in bio-medicine as well as health care management. In bio-medicine domain, there are ontologies for general medical science (e.g., the Gene ontology and the foundational model of anatomy ontology).

Actor profile ontology [10] formalizes organizational health care knowledge for home care and represents the concepts of main entities involved in Home Care (e.g., actor, medical service/procedure, action, documents) as well as the relationships among them and profile-related restrictions. A framework of *healthcare ontology* describes a workflow of overall health care service delivery, including healthcare processes, resources, organizations, and policies in a hospital environment [11]. In this framework, the ontology captures all necessary knowledge for a complex personalized healthcare scenario involving patient care, insurance policies, and drug prescriptions, and compliances.

Case profile ontology [12] defines chronically ill patient health conditions and intervention plan to make better decision from the perspective of healthcare professionals and practitioners. In this ontology, patient health conditions are classified as 1) 19 diseases (e.g. anemia, arthritis, depression, diabetes, etc.), 2) 2 syndrome (e.g. immobility, cognitive impairment), and 3) 5 social issues (e.g. mental illness, low income, lack of social network, etc.). Interventions are classified into 1) pharmacological treatments, 2) non-pharmacological treatments, 3) rehabilitation, 4) nursing care, 5) social care, 6) counseling and 7) special medical services.

An *ontology of mHealth* [13] articulates the logic of mobile Health(mHealth) domain by adopting the information system terminology of mHealth. There are three major dimensions: 1) mHealth system, 2) stakeholders, and 3) the outcomes. For further detailed construction of the ontology, the dimension of mHealth system has 1) structure, 2) function, and 3) semiotics as sub-dimensions.

As more specific ontologies to manage personal health, the *PerKAfopp ontology*[14] represents specifically the food properties in a context of healthy life involved in physical activity and diet. The main concepts of this ontology are 1) food, 2) nutrient, 3) timespan and 4) meal. *Ontologies of behavior changes* [15] emphasizes more on knowledge discovery in behavior science such as behavior change interventions and Behavior Change Techniques (BCT) taxonomy. This ontology has 6 main classes based on the study [16]: 1) Intervention, 2)Usage, 3) Context, 4) Mechanism of Action, 5)Behavior, and 6) Effect. The *Self-Management Program Personalization (SPP) ontology* [17] integrates validated health assessment tools, social cognitive theory (SCT) based behavior models, and self-management strategies and messages in a context of mHealth. There are 6 high level concepts: 1) individual profile, 2) goals, 3) barriers, 4) intervention intent, 5) strategy, and 6) message. However, the ontologies in this context focus on extracting and aggregating the terms for creating the taxonomy, not for formulating the rules, given captured terms.

As aforementioned, there are several limitations in healthcare domain ontologies. First, not many ontologies attempt to conceptualize semantic information particularly in personal health management from a person-centered perspective. Secondly, since healthcare ontologies are used in many different contexts, it is difficult to unify and classify a variety of terminologies for shared conceptualization. For examples, Accordingly, some concepts that have possibly same meaning are described by different terms and vice versa. Such complexity and inconsistency in matching terms and concepts from different healthcare contexts impedes effective knowledge accumulation, rule formulation and further reusability of ontologies. On the other hand, there is a great potential to map and merge multiple healthcare ontologies for creating an ontology that can harmonize and accommodate any subtle differences in concepts and instances through reusing the existing ontologies and developing a systematic way to classify multidisciplinary knowledge for person-centered health process management.

2.3. Ontology design patterns

Ontology engineering requires substantial efforts in discovering logical and content patterns for conceptualization and axiomatization using

Web Ontology Language (OWL) [18]. Ontology Design Patterns (ODPs) were introduced by Gangemi [19], as a means of simplifying ontology development with a generic recurring construct. In the ODPs, the encoding of conceptual design pattern uses small reusable blocks of functionality that are domain independent – Generic Use Case (GUC). Such construct can be adapted and specialized for more specific patterns in individual ontology development projects. As an ontology engineering tool, ODPs have benefits as follows[20]:

- ODPs can be reused directly using the implementation language (e.g., OWL) in terms of abstract ideas and actual components.
- ODPs can have a certain level of interoperability in integrating multiple datasets, due to the minimal ontological commitment and reuse of the same ODP in conceptualization.

For example, an application for planning-activity can use Action ODP, planning ODP, and even ODP, which are available in the ODP portal (http://ontologydesignpatterns.org). For tracking and recording activities defined by a plan, Province ontology (PROV-O) [21] can be used with the patterns in entities, activities, and agents in generating, influencing, or delivering the data. PROV-O can be applied and modified in describing the changes of the activities of entities in ubiquitous sensor networks and Internet of Things (IoT) such as activity-based personal information management, human trajectory modeling [22], or ambient assisted living (AAL) [23], [24]. Eventually it enables semantic annotation in human activity data as well as information retrieval and automatic reasoning.

3. Proposed ontological approach

In this paper, we propose an ontological approach to provide an adaptive and personalized improvement path for person-centered health process management as a part of PHMS that is integrated with bio-sensors and IoT, using mobile or/and web-based application. Figure 1. depicts the conceptual model of ontological approach in PHMS. The data from a user, mobile apps, and bio-sensors are collected and stored in cloud storage for accessing and sharing purposes as well as in the database server for interfacing with knowledge base and rule-inference engines. Knowledge base and rule-inference engines are to construct health improvement path for monitoring and assessing progress of the user's health status and lifestyle.

3.1. Health Capability Maturity Model

In this ontological approach, HCMM[25] is a core concept for a customized roadmap that includes a set of health goals and their associated activities for self-management in health improvement. Based on health behavior change and self-management, the capability level and the maturity level are defined as follows:

- *Capability Level*: the degree of an individual's health literacy and ability to obtain, process, understand, and communicate health-related information and activities that are required to make informed health decision [26], [27]. It is a level of knowledge, skills, and health management process ability of an individual to perform behavior change activities for one's health improvement.
- *Maturity Level*: the extent to which a set of specific health management areas is explicitly defined, managed, measured, and controlled by an individual to perform behavior change activities[28], [29]. It is a level of an individual's commitment to pursue and

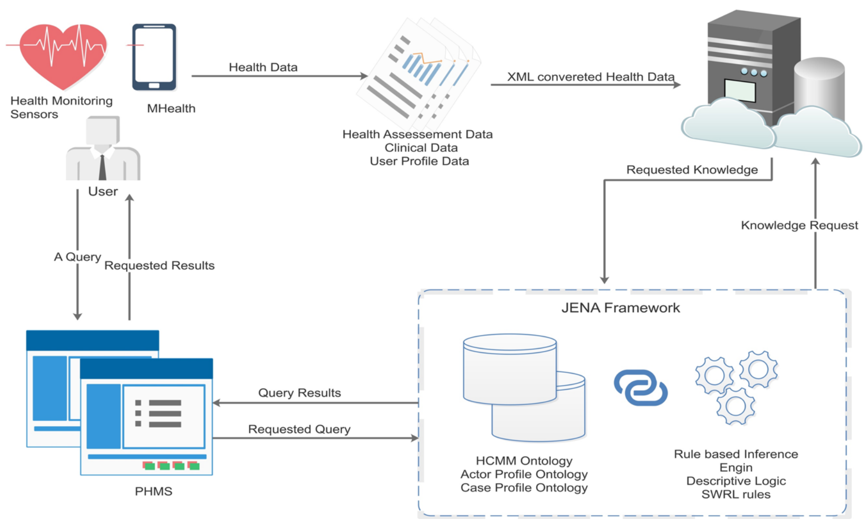

Figure 1. A proposed architecture of ontological approach in PHMS

maintain behavior change activities for one's health improvement.

3.2. PHM process areas and level definition

An PHM process area is a cluster of practices that are associated with health goals and activities in HCMM. PHM areas address the health dimensions that are grounded on personal health assessment and self-management/care program: diet, emotional health, health literacy, health status, medication, physical activity, and self-efficacy[30],[31].

In the proposed ontological approach, five process areas are classified: *Health Evaluation, Health Education, Health Control, Health Monitor, Health Quantitative Process Management*, and *Health Promotion*. Each PHM process area is aligned with recommended pre-defined goals that help an individual establish the patterns of health behavior and enhance capability in self-management. To acquire each maturity level or advance to the next level, the individual should accomplish a set of goals in PHM process areas defined by each level as requirements. HCMM's levels are defined as follows:

- *Level 0*: no or lack of health self-management practices and basic skills, knowledge, and motivation.
- *Level 1*: intention to change, awareness of the pros and cons of change, and ability to repeat routinely recommended health practices.
- *Level 2*: ability to conduct significant actions of a plan for adopting a care plan and to establish the defined PHM process areas.
- *Level 3*: ability to makes modification in lifestyle and use quantitative analysis for self-monitoring and controlling performance.
- *Level 4*: ability to prevent relapse and continuously improve the performance.

3.3. HCMM ontology

In terms of the basic structure, HCMM ontology adopts and reuses the CMMI ontology[32], [33], a reference model to describe software engineering process management. However, except for applying the concepts and relations of capability and maturity levels, HCMM ontology has been largely tailored to the domain-specific context – health self-management and behavior change management in healthcare. HCMM ontology is used to build a knowledge base for constructing personalized health improvement plans given a choice of representation. In addition to the plan, HCMM ontology merges and maps concepts of health management process with other relevant ontologies in health domains for supporting reusability and scalability. For example, Actor Profile Ontology [10] or Case Profile Ontology [12] can be reused for an individual's health profile. BCT ontology [15] is for PHM process area and health goals. For using reusable blocks in ODP, Activity Reasoning [22] and P-Plan ontology [34] are referenced.

To detect and generalize the requirements for HCMM ontology, the following competency questions(CQ) include:

- CQ1: what are PHM process areas in each maturity level?
- CQ2: what goals need to be achieved in order to satisfy each maturity level?
- CQ3: what goals are associated with PHM process area?
- CQ4: what practices need to be achieved in order to satisfy each goal?
- CQ5: what level should be completed before this maturity level?

Figure 2. denotes HCMM ontology model for the conceptualization of personal health improvement process. After health level assessment and identification, the workflow starts with the selection of health improvement path representation: *continuous* and *staged. Continuous* representation is for achieving health goals by focusing on a capability level as a way of satisfying PHM process areas selected by an individual. *Staged* representation is to achieve the health goals by focusing on a maturity level stage by stage as a way of satisfying all the pre-defined health goals in PHM process areas of a level. Given a selected level of capability or maturity, target PHM process areas are listed with health goals.

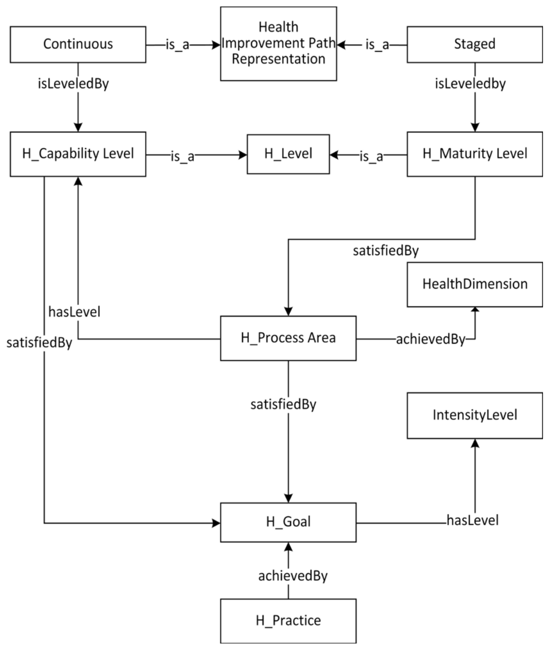

Figure 2. HCMM Ontology Model

The relations in HCMM ontology and their meanings are listed below. HCMM ontology is built with Protégé[35], an open-source ontology editor and knowledge-bases framework as shown in Figure 3.

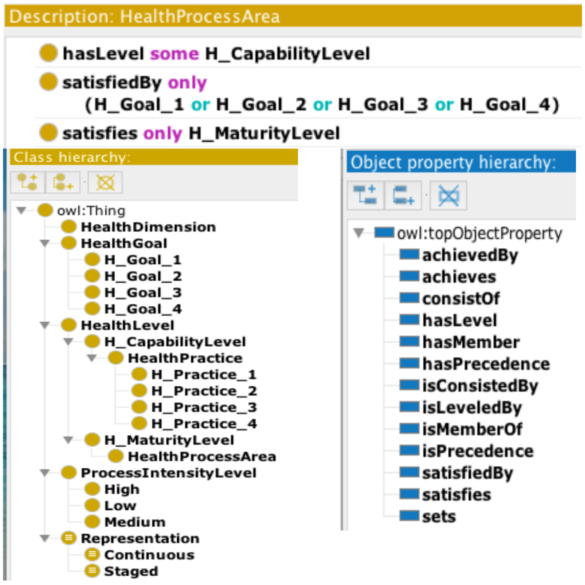

Figure 3. Screenshot of HCMM ontology in Protégé

- **is_a** : All is-a relations demonstrate the superclass-subclass relationship between the classes. For instance, a class *HealthLevel* is an superclass of *H_CapabilityLevel* and *H_MaturityLevel* .
- **isLeveledBy**: Either *Continuous* or *Staged* representation class sets an improvement path, starting with *Health Level*. *Health Level* has two subclasses: *H_CapabilityLevel* and *H_MaturityLevel*. *Continuous* represnetaion is leveled by *H_CapabilityLevel* and *Staged* representation is leveled by *H_MaturityLevel*.
- **achieves/achievedBy**: A health goal is satisfied if all its associated practices are achieved. The relations are between *HealthGoal* and *HealthPractice* classes.
- **hasLevel**: a class *Person* has a *H_MaturityLevel.* A class *H_ProcessArea* has *H_CapabilityLevel.* Also, a class *HealthGoal* has a level with a class *intensityLevel: Low*, *Medium,* and *High.*
- **hasPrecedence/isPrecedence**: An achievement of *HealthLevel* requires completing all previous levels, which is demonstrated by *hasPrecendence/isPrecendece* relations. *isPrecedene* is an inverse property of *hasPrecedence*. For instance, *Capabilty_3* has precedences *Capabiltiy_0, Capabiltiy_1*, and *Capbilty_2.*
- **satisfies/satisfiedBy**: For a person to achieve a maturity level, *H_maturityLevel* should be satisfied by *H_processArea*. For a person to obtain a capability level, *H_capablityLevel* should be satisfied by a class *HealthGoal*.

3.4. Merged and aligned HCMM ontology with existing ontologies

One of the main benefits of an ontology is reusability by sharing and exchanging knowledge with other existing ontologies. Since HCMM ontology is a reference model to define the structure of health self-management process areas, each PHM process area can be merged and aligned with the existing healthcare related ontologies. For instance, Concepts in International Classification of Wellness (ICW) ontology (https://bioportal.bioontology.org/ontologies/ICW) can be reused for health process areas in HCMM ontology as mentioned in section 3.2. *Health Control* and *Health Monitor* are associated with wellness activities of an individual. In particular, these two process areas consist of physical wellness including diet, fitness, therapy and preventions as defined in ICW ontology. The query result in Figure 4. displays which process areas consists of diet or physical wellness and its corresponding activities.

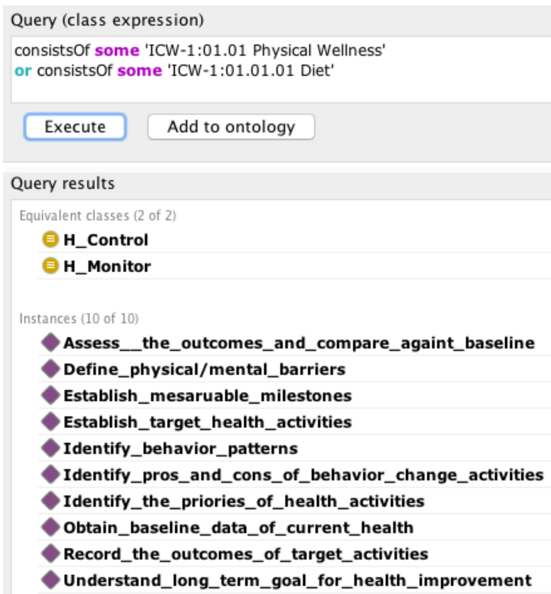

Figure 4. Screenshot of HCMM ontology merged with ICW ontology

3.5. Rules reasoning and query

We adopt a rule-based approach, which includes two types of reasoning: ontology-based inference and user-defined inference. Both are implemented as a rule-based inference engine. Ontology-based reasoning in Descriptive Logic (DL) can be used to determine concepts[36]. User-defined rules in Semantic Web Rule Language (SWRL) [37] provides more flexible expression to make inference over the ontology knowledge base and complement the limitation of DL. SPARQL Protocol and RDF Query Language (SPAQL) [38] is used to retrieve and infer the information. SPAQL queries determines which health goals a user should complete, given a desired maturity level and what PHM process areas a user needs for reaching to the desired maturity level, and so on. Figure 5. displays the required goals in *Health Process Area* (e.g., *Health Education, Health Promotion*, or *Health Monitor*) that should be accomplished for maturity level 1.

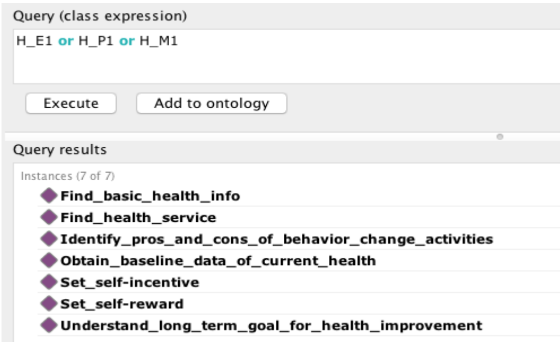

Figure 5. DL query result

Figure 6. depicts a level 1 data flow diagram of how user input data are transformed into a health maturity level of the user and the personalized health improvement paths. The process 1 is used to determine a user's health maturity level by using health assessment questionnaire result and user's profile. In the process 2, the assessed health maturity level of the user and the user's desired health improvement goal are used to construct health improvement plan (HIP). HIP is calculated using semantic queries using HCMM and HCMM rules. The calculated HIP and the user's personal lifestyle information such as time to get up and time to sleep, are provided to the process 3. The desired health improvement paths are calculated, given all the inputs from users and HCMM rules. Once the paths are defined, user's daily activities and other action items specified by HCMM are monitored, and the data are collected and assessed by mobile devices such as smartphone, smart watch, etc. Daily assessment result is reported back to the user in compliance with the personalized HIP and give possible recommendations and notifications such as a rate of completion, a status message or a nudging message.

4. Conclusion and future work

PHMS has great potential for individuals to improve outcomes on their health. However, there exist substantial variability in behavioral, personal, and environmental factors in achieving personal health improvement. Our proposed ontological HCMM approach addresses such issues by focusing on PHM processes and providing customized health improvement path(s) for an individual's health self-care management. The contributions of this approach can be summarized as follows: First, as a generic model, HCMM ontology describes higher-level requirements and constraints that are associated with PHM processes. Secondly, HCMM ontology is a top-down approach to the health management process, which can be easily narrowed

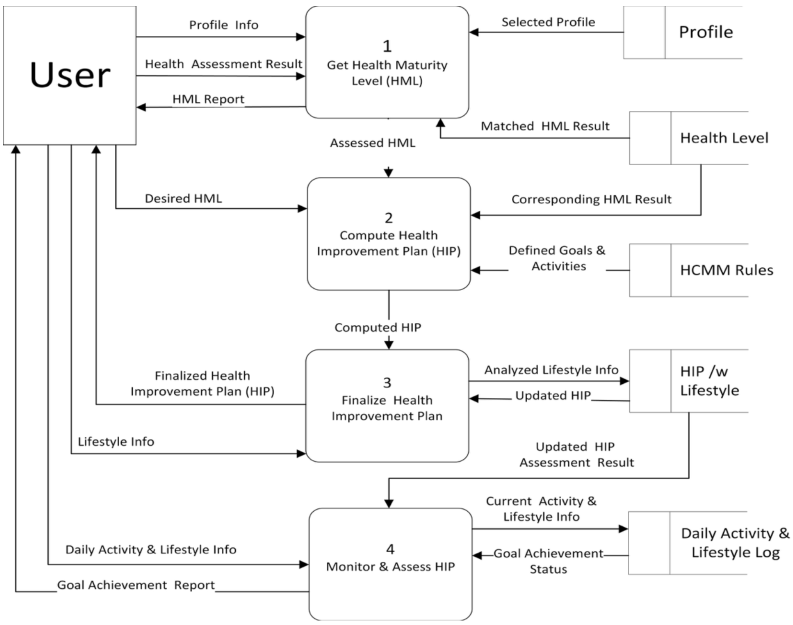

Figure 6. Health improvement path calculation

down to specific use cases, and aligned and merged with other healthcare ontologies for effective reusability and scalability. Finally, HCMM knowledge base and rule-inference engines facilitate the collected data with user inputs and queries and formulate multiple possible health improvement plans, which pursues the purpose of engaging an individual more actively in one's health self-management.

Since it is desirable to have a fully automated framework, we plan to complete automation of the process and incorporate more detailed activities in each level of HCMM as our future work. Additionally, the existing ontologies related to self- management will be integrated with HCMM ontology to provide more domain-specific conceptualization and axiomatization. Ontology evaluation is very critical in validating whether an ontology has been built to meet the application requirements. HCMM ontology has been initially evaluated by OntOlogy Pitfall Scanner! (OOPS!) [39], a globally adopted tool for detecting pitfalls in ontologies and no major issues have been detected. However, it is still necessary to validate HCMM with domain experts and ontology engineers for improving the quality of ontologies.

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